Model Color-Magnitude Diagrams for HST Observations of Local Group Dwarf Galaxies

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ABSTRACT

In this paper, we discuss a method to conduct a quantitative study of the star formation history (SFH) of Local Group (LG) galaxies using Hubble Space Telescope (HST) data. This method has proven to be successful in the analysis of the SFH of the same kind of galaxies using ground-based observations. It is based on the comparison of observed CMDs with a set of model CMDs. The latter are computed assuming different evolutionary scenarios, and include a detailed simulation of observational effects.

CMDs obtained with HST are ~ 3 mags deeper than typical CMDs obtained from ground-based telescopes, allowing the observation, for all LG galaxies, of a part of the CMD that up till now had remained accessible only for the very nearest galaxies. A very important feature that will become accessible with HST is the horizontal-branch *plus* the red-clump. The distribution of stars along this structure is quite sensitive to age and metallicity and should provide a very important improvement in the time resolution of the SFH for stars older than $\simeq 2-3$ Gyr. We show and discuss four model CMDs which would be comparable with CMDs from deep HST observations. These model CMDs represent the following evolutionary scenarios corresponding to a wide range of dwarf galaxy sub-types from dI to dE: **A)** a constant SFR from 15 Gyr

ago to the present time; **B)** as A), but with the SFR stopped 0.5 Gyr ago; **C)** a constant SFR in the age range 10-9 Gyr and **D)** as C) but in the age range 15-12 Gyr. In all four cases a range of metallicity from $Z = 0.0001$ to $Z = 0.004$ has been assumed.

The present analysis is just a first qualitative approach to what one may expect to find in the CMDs of LG galaxies. However a complete set of model CMDs must be computed to analize the data for each galaxy, using the crowding effects derived for that particular galaxy.

Subject headings: Galaxies: elliptical — Galaxies: irregular — Galaxies: stellar content — HR diagram — Local Group

1. Introduction

The most powerful way of studying stellar populations and the star formation history (SFH) of a galaxy is by means of the analysis of the distribution of stars in the color magnitude diagram (CMD). This kind of study can only be performed for systems close enough for their stars to be resolved and has usually been limited to Local Group (LG) galaxies. It has been shown that the SFH of a LG galaxy can be fully determined from the analysis of its CMD, using model CMDs based on synthetic ones in which a careful simulation of observational effects is performed. Full SFHs, from the present to the very early episodes of star formation which took place more than 10 Gyr ago, have been obtained using this method for NGC 6822 (Gallart et al. 1996b, 1996c), Pegasus (Aparicio, Gallart & Bertelli 1996a) and LGS 3 (Aparicio, Gallart & Bertelli 1996b).

Nevertheless, the ability to resolve the short time scale structure in the SFH necessarily worsens for older and older ages. Observation of the horizontal-branch (HB) and the red-clump (RC) of core He-burning stars is crucial to improve the time resolution for ages in the range from a few Gyr to the oldest ones. The distribution of stars in these structures will also provide constraints on the chemical enrichment law (CEL) at intermediate and old ages. The HB and RC have been observed for the nearest Milky Way satellites using ground-based telescopes, but are unreachable from the ground for more distant galaxies, including the rest of the LG members. However, it is expected that these structures will be observed in deep HST's images for any LG galaxy. These images would also contain important clues for young stars in the main-sequence (MS) and blue-loop (BL) phases, at ages up to ~ 1 Gyr. As in the case of the HB and RC, these stars are only accessible for the Milky Way satellites from ground-based telescopes.

In this paper we present a guideline of how the method we have used for several LG galaxies observed from the ground, can be applied to HST observations of dwarf galaxies up to a distance of 1-2 Mpc. Based on model CMDs, we show the distribution of stars to be expected for four different cases of SFH: **A)** a constant star formation rate (SFR) from 15 Gyr ago to the present time; **B)** as A), but assuming the star formation ceased 0.5 Gyr ago; **C)** a constant SFR at ages 10-9 Gyr and **D)** as C) but at ages 15-12 Gyr. In all four cases a range of metallicities from $Z = 0.0001$ to $Z = 0.004$ has been assumed. The first two cases, A) and B) may be representative of what can be expected for a dI galaxy or a dI-dE intermediate case such as LGS 3, whereas C) and D) might be representative of a dE galaxy in which no star formation has occurred since several Gyr ago.

Section 2 presents the model CMDs. In Section 3 we discuss the different features of those diagrams, and in Section 4 we summarize the conclusions.

2. The Model Color Magnitude Diagrams

The construction of a model CMD comprises two steps: *(i)* computation of a synthetic CMD and *(ii)* simulation of observational effects. Synthetic CMDs are based on a set of stellar evolutionary models covering the required range of masses and metallicities. The Padua stellar evolutionary library has been used here (see Bertelli et al. 1994 and references therein). The basic hypothesis under which a synthetic CM diagram is generated are an input SFR and CEL both as a function of time. The initial mass function (IMF) is also input information which we choose to maintain unchanged in all our models. In particular, we used the IMF derived by Kroupa, Tout & Gilmore (1993). Synthetic CMDs reproduce the distribution of stars for different input SFR and CEL and other intervening functions and parameters which we have kept fixed here. But these diagrams cannot be compared directly with the observed CMD since the latter include the observational effects resulting mainly from stellar crowding. In spite of the much better spatial resolution of HST, crowding is expected to play the main role imposing a limit to the photometry, affecting also its quality, especially near the limiting magnitude, where the HB and the RC will be located. In this way, careful simulation of crowding effects is also needed to correctly interpret HST data, as will be shown below. Crowding effects are of three kinds: *i)* a fraction of stars are lost, *ii)* magnitudes and color indices are systematically shifted and *iii)* affected by large external errors. The three effects are strong, non trivial functions of the magnitude and color index of each star and of the distribution of magnitudes and color indices of all the stars present in the galaxy (see Aparicio & Gallart 1995 and Gallart, Aparicio & Vílchez 1996a). We term synthetic CMD, the diagram prior to the simulation

of observational effects, and model CMD the synthetic CMD after simulating those effects.

For the present analysis, synthetic and model CMDs have been obtained as described in Aparicio & Gallart (1995) and Gallart et al. (1996b). Four synthetic CMDs have been initially computed using the ZVAR code (see Chiosi, Bertelli & Bressan 1988 for a discussion of an early version of it) and assuming a constant SFR; a linear CEL with initial metallicity $Z_i = 0.0001$ and final metallicity $Z_f = 0.004$, and the following values for T_i, T_f (starting and final times for the star formation):

A) $T_i = 15$ Gyr, $T_f = 10^{-2}$ Gyr

B) $T_i = 15$ Gyr, $T_f = 0.5$ Gyr

C) $T_i = 10$ Gyr, $T_f = 9$ Gyr

D) $T_i = 15$ Gyr, $T_f = 12$ Gyr

where time is expressed in terms of age, i.e. increasing towards the past, 0 denoting the present moment. Using the relation by Nissen & Shuster (1991) and $Z_\odot = 0.02$, the adopted range of metallicity $Z = 0.0001$ to $Z = 0.004$ corresponds to $[Fe/H] = -2.7$ to –1.1.

The observational errors have then been simulated in the synthetic CMD using the crowding test table obtained in the analysis of NGC 6822 by Gallart et al. (1996a), but with a different zero-point, such that the crowding effects for the hypothetical HST observations at a given stellar magnitude were the same as for the ground-based telescope (the 2.5 m INT at Roque de los Muchachos Observatory) for stars 3 magnitudes brighter.

Figure 1 shows the synthetic CMD for case A as a reference, since Figure 2 shows the final model CMDs for cases A, B, C and D respectively.

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3. Discussion

Figure 1 shows the synthetic CMD -prior to the simulation of crowding- with the 50000 stars used for case A. The main features present in the diagram are the MS, BL sequence and RGB, together with an HB finishing in a RC at its red edge, and an AGB red-tail

structure. The single star at $I \simeq -6$, $(V-I) \simeq 2$ is a younger AGB, whereas the brightest stars at $(V-I) \simeq 1.0$ to 1.5 are RSGs. The tip of the RGB can be seen at $I \simeq -4.0$ and $(V-I) \simeq 1.2$ to 1.7. A number of red subgiant stars evolving from the MS to the RGB are apparent between these two sequences, below the HB. The synthetic diagrams for cases B, C and D lack the structures formed by young stars: MS, blue-loops, RSG and a part of AGBs. These diagrams are not shown for simplicity.

Model CMD A (Figure 2a) is representative of what we should expect to see in a dI galaxy at about 1Mpc. A constant SFR and an early age for the beginning of star formation have been assumed as a representative SFH for a dI galaxy according to the results reported by Gallart et al. (1996b) for NGC 6822 and Aparicio et al (1996a) for Pegasus. In that paper it is shown that NGC 6822 most likely began to form stars at a very early epoch (about 15–12 Gyr ago), from low metallicity gas, and that a SFR close to constant or declining in the last few Gyrs seems best to reproduce the observations. Figure 2a shows the result of simulating observational effects in the synthetic CMD of Figure 1: many stars in the faintest magnitude interval are lost and the MS and RGB are widen at their lower part. This also affects the HB, which becomes completely diffused into the noisy tails of the MS and RGB. This is an important point, meaning not only that long integration times will be needed to observe the HB and RC even for the nearest dIs, but also that the limiting magnitude will be imposed by crowding. This implies that if the SFH is to be retrieved by comparing the observed CMD with model CMDs, an accurate simulation of crowding effects is required as in the case of ground-based observations.

The fact that the BL sequence is clearly resolved from the MS is an interesting feature of Figure 2a. This is not usually the case for ground-based observations, due to the worse crowding but also because Figure 2a shows less massive stars than common ground-based works and the gap between the MS and the BL is larger for these stars. Finally, structures already observed from the ground, like the red-tail, are also present in the CMD of Figure 2a and they preserve their power in the determination of the SFH. Note that the small field of the WFPC2 would result in a poor sampling of fast, hence low populated stellar evolutionary phases, like the upper MS and BL, the RSG and the AGB, including the red-tail itself. The relevance of these structures in the determination of the young SFH (MS, BL and RSG) and the full SFH (AGB and red-tail) is so important that mosaics of a number of WFPC2 frames or complementary ground-based, large field observations should be considered in the observational strategy if a quantitative derivation of the SFH is intended.

Model CMD B (Figure 2b) is meant to represent a limiting case of a hypothetical dI galaxy where star formation has stopped five hundred million years ago, or a dE galaxy

with a considerable amount of intermediate-age or even young stars. LGS 3 (Aparicio et al 1996b) or Leo I (Lee et al. 1993) seem to be good examples of this intermediate type of galaxy. The very young population (MS, bright blue-loops and RSG) present in model A has disappeared here, but a large number of stars populate the lower part of the diagram from $(V-I)=-0.2$ to 1.2. They are MS and subgiant stars (but also the result of crowding which, in our models, is significant at this magnitude level) and they mask the HB almost completely so much so that it becomes hardly distinguishable. This is an important point because the lack of a blue HB would be interpreted as the lack of either very old or very low metallicity stars. Nevertheless, if the simulation of crowding effects is accurate enough, a detailed comparison of the distribution of stars in the observed and model CMDs will show the presence of the HB and still allow valuable information to be obtained from it. The small group of stars over the red-clump, at $(V-I)\simeq 0.85$ and I from –1 to –2, is produced by stars with ages between 0.5 and 1 Gyr undergoing the nuclear He-burning phase.

Model CMDs C and D (Figure 2c and 2d) are hypothetical representations of dE galaxies with no star formation activity over the past 9 Gyr (model C) and 12 Gyr (model D). There are several indications about the existence of intermediate populations in dE. For some dE companions of the Milky Way, like Carina (Mould & Aaronson 1983; Mighell 1990 and Smecker-Hane et al. 1996), Leo I (Lee et al. 1993) and Leo II (Mighell & Rich 1996), the deep CMD obtained from the ground clearly show this. But for more distant systems, like the Andromeda companions, the controversy about the existence or not of a substantial amount of intermediate-age star formation is an open question (Mould & Kristian 1990; Freedman 1992; Lee, Freedman & Madore 1993; Konig et al. 1993; Armandroff et al. 1993). In this sense models B and C can be used to test whether or not an intermediate-age population exists in a given galaxy.

Star formation occurred from 10 to 9 Gyr ago in model C, and from 15 to 12 Gyr ago in model D, with the same range of metallicities from $Z_i = 0.0001$ to $Z_f = 0.004$ in both cases. The RGB locus is the most apparent feature in both CMDs, together with an HB+RC structure. In fact, the most evident difference between the diagrams of models C and D is the extension of the HB, solely due to the different ranges of stellar ages. Since the metallicity range can be confidently determined from the dispersion of the upper part of the RGB, where crowding effects are small (in fact there is practically no difference between the synthetic CMDs and the model diagrams in that area), the extension of the HB is crucial when determining of the age of the oldest stars in the system. Finally a few AGB stars are observed over the tip of the RGB, forming a red-tail structure in both models.

An interesting difference between models A and B and models C and D is the width of the RGB, although in all cases the range of metallicities is the same. This is due to the

effects of age and metallicity moving the stars' colors in opposite senses. Therefore, care must be taken when interpreting the width of the RGB as an indicator of the metallicity dispersion, unless independent proof of the age dispersion is available. With less deep observations than those modelled here, a hypothetical galaxy with a SFH equal to that portrayed in case B would be virtually undistinguishable from case C or D. If the absence of young stars populating the observed part of the CM diagram were interpreted as the galaxy being a pure old system, the RGB's width would be produced by the star's metallicity dispersion, leading to a much smaller value for that dispersion than the actual one, and therefore, an evolutionary scenario notably different from the real one would be inferred.

We have discussed four realistic examples of what can be expected from observations using HST for LG dwarf galaxies. But to quantitatively retrieve the SFH of a real galaxy would require a complete set of synthetic CMDs assuming different evolutionary scenarios (SFR + CEL basically) to be computed. Crowding effects for that particular set of observations should be derived and then simulated in the synthetic CMDs to obtain a set of model CMDs directly comparable to the observed CMD. However, in the light of the new photometric material that HST is producing, the four particular examples shown in this paper may help to gain an initial qualitative understanding of the stellar populations present in a galaxy.

4. Conclusions

Comparison of model CMDs with observed CMDs is a powerful tool to quantitatively obtain the SFH of a given galaxy. Deep observations using HST will reveal two structures, the HB and the RC, which to date could be only observed in the nearby satellites of the Milky Way. Their analysis will definitively allow the full SFH of these galaxies to be obtained accurately, with much higher resolution towards old ages than the SFH obtained up till now from ground-based observations.

To illustrate what can be obtained from long integrations with HST for galaxies at a distance of about 1 Mpc, four examples of model CMDs, for four different SFHs, have been presented and discussed. These model CMDs can be considered as first approachs to the CMD of a dI galaxy (model A), an intermediate case between dI and dE (model B) and two cases for dE galaxies with no star formation since several Gyrs ago (models C and D). The HB+RC structure is clearly visible in cases C and D and promises to be particularly powerful in the detailed determination of the intermediate-age and old SFH. Long integration times seem necessary to detect them with good signal to noise ratio. However the HB is hardly visible in models A and B where they appear embedded in

the diffuse cloud produced by crowded MS, RGB and subgiant stars. Nevertheless, if the simulation of crowding effects is accurate enough, a detailed comparison of the distribution of stars in the observed and model CMDs may still yield valuable information.

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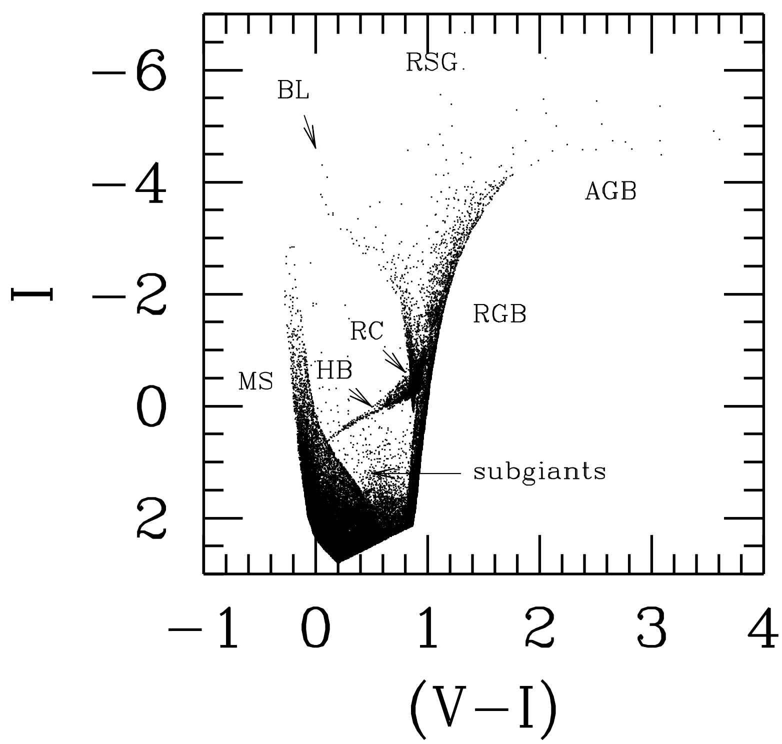
Fig. 1.— Synthetic CMD for constant SFR, $T_i = 15$ Gyr, $T_f = 10^{-2}$ Gyr, $Z_i = 0.0001$ and $Z_f = 0.004$.

Fig. 2.— CMDs for the four model SFH discussed. Constant SFR and initial and final metallicities $Z_i = 0.0001$, $Z_f = 0.004$ are common to the four models. The time marking the beginning of the star formation is $T_i = 15$ Gyr for models A, B and D, and $T_i = 10$ Gyr for model C. The time marking the end of star formation is $T_f = 10^{-2}$ Gyr for model A; $T_f = 0.5$ Gyr for model B; $T_f = 9$ Gyr for model C and $T_f = 12$ Gyr for model D. $T = 0$ is the present time.



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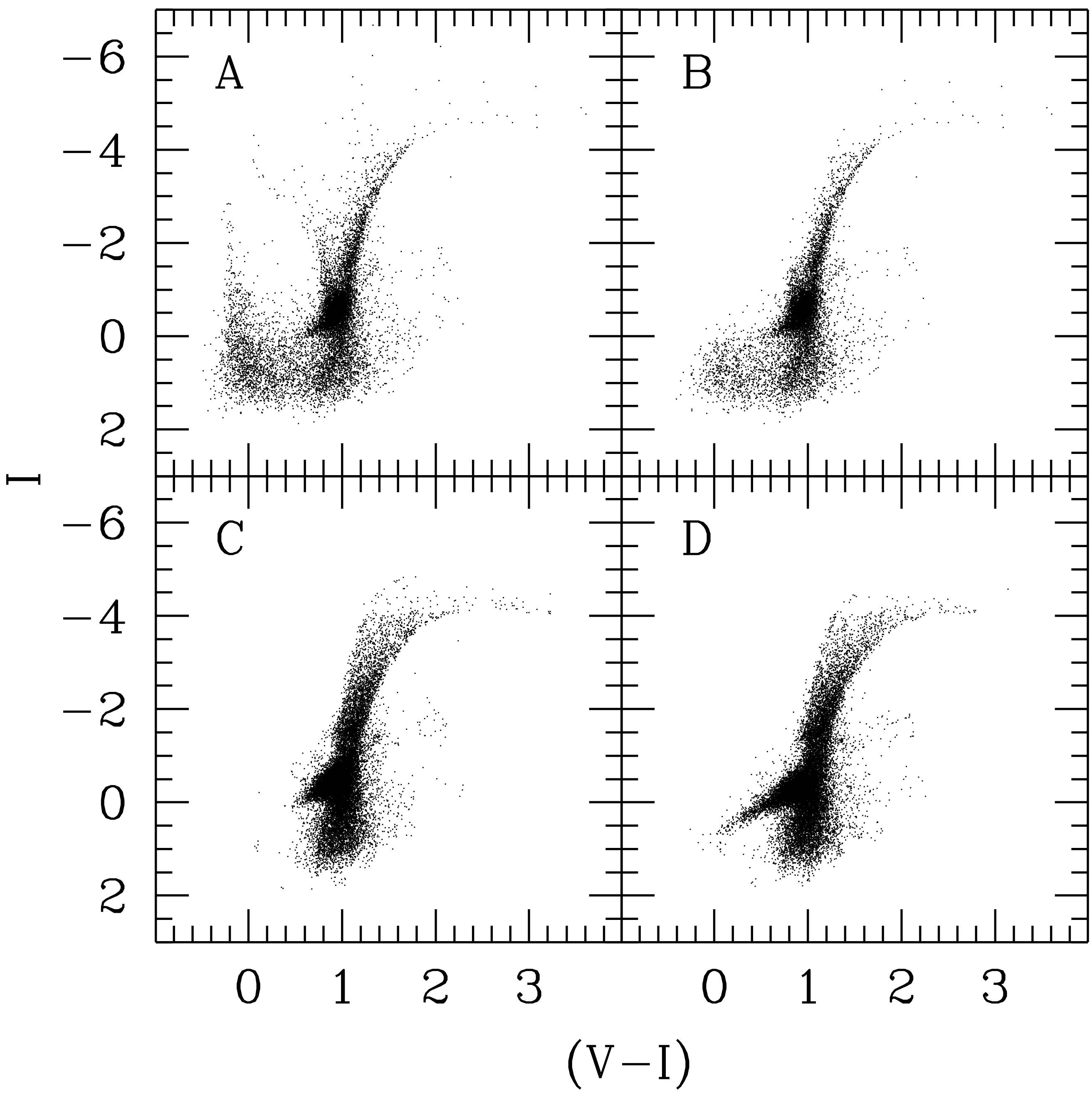
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